Evaluation of the State of Passive UHF RFID: An Experimental Approach

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***Abstract*—In this paper, we identify the state of the technical capability of passive UHF RFID tags and readers using a simple, empirical, experimental approach. This paper does not focus on theoretical capabilities of RFID systems in ideal environments, but rather a pragmatic evaluation of the state of commercially available ISO 18000-6c systems and identifying areas where there are opportunities for improvements in the technology. We examine the free-space read distance of tags by readers, near-metal read distance, near-water read distance, frequency-dependence of read distance in those environments, near-field read distance in those environments, read speeds, and a determination of forward or reverse channel limits.**

***Index Terms*—Measurement, near field, performance, RFID, RFID readers, RFID tags.**

I. Introduction

PASSIVE RFID has been used for decades, but recent developments in the scale and costs of passive UHF RFID tags, with their widespread adoption within the supply chain, has caused explosive growth in its application. It is important for the community to understand the capabilities and limitations of the technology, and just as importantly, understand where researchers may contribute to the improvement in the technology.

Recent mandates in the retail and government sector have created new demands for passive UHF RFID technology. The primary benefits of RFID are: large ID numbers (96 bits is typical), which allows every item to have a unique ID; rapid identification of large numbers of tags, which is useful for automatically reading cases on pallets; does not require line-of-sight, which means the tags may be encapsulated or still readable when hidden; some security features such as password protected operations, which makes counterfeiting more difficult; and widespread global adoption around a well-established standard [1]. UHF has an advantage over the more established HF and LF technology in that the read distances can be considerably longer. Typically, HF and LF technology uses (nonpropagating) inductive coupling, while UHF uses (propogating) electromagnetic coupling. The longer read distances enable new use cases, such as scanning items as they pass through large portals such as dock doors. Furthermore, the antenna designs for UHF tags are commonly based on a dipole design that is typically long and thin, which simplifies manufacturing compared to multiple loop antennas that require a crossover component. The higher frequencies also allow the use of thinner and/or less conductive material for the antenna, which can reduce costs. The lowest known published cost of a functional UHF RFID tag as of April 2007 is less than $0.07 US dollars.

In this paper, we identify the state of the technical capability of passive UHF RFID tags and readers using a simple, empirical, experimental approach. Using well known principles and "conventional wisdom" in the community, we form hypothesis about how tags and readers will perform. (We determine "conventional wisdom" from discussions with a number of practitioners in the field.) We devise experiments to test these hypotheses. Sometimes we find the hypotheses correct, and other times we find them incorrect and devise follow-on experiments to further determine function. Ideally, we could measure tag and reader performance directly and sufficiently using simple metrics such as antenna gain, impedance matching, modulation depth, and SNR, but experience has shown that performance is far more complex. Since tags and readers work as a system, and, as we show through experimentation in this paper, there is a complex interaction between the two, we use tags to test readers and readers to test tags. These experiments are purposefully simple and designed so that they may be readily replicated, yet carefully constructed to reveal some important aspects about the tag-reader system performance. We examine the free-space read distance of tags by readers, near-metal read distance, near-water read distance, frequency-dependence of read distance in those environments, near-field read distance in those environments, read speeds, and a determination of forward or reverse channel limits.

This paper is organized as follows. In Section II, we give some background information that will be used throughout the paper. In Sections III and IV, we examine how tag performance is affected by the proximity of metal and water, respectively. We repeat those experiments using a different method in Section V and compare the results of the two methods. In Section VI, we explore the performance of the relatively new area of near-field UHF tag performance. Next, in Section VII, we briefly examine the bandwidth limitations of RFID tags. In Section VIII, we take an extensive look at UHF RFID readers. We summarize our findings and conclusions in Section IX.

II. Background

Much work has gone in to developing and evaluating UHF RFID tag technology. This paper is not focused on the theoretical capabilities of RFID systems in ideal environments,

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Fig. 1. Example of a meandering dipole antenna for a UHF RFID tags (author's design).

but rather on a pragmatic evaluation of the state of commercially available ISO 18000-6c systems and identifying areas where there are opportunities for improvements in the technology. Similar work has been performed [2], [3], focusing on developing benchmarks. In contrast, this work focuses on identifying the larger trends in the technology rather than the performance of specific products.

The two primary components that make up an RFID system are the transponders (or "tags") and interrogators (or "readers"). An RFID tag is *passive* if it has no internal power source. Passive tags use energy harvesting to supply power to the internal circuitry and backscatter modulation to communicate to the reader. The air interface, protocol, numbering convention, reader air position indicator (API), and network lookup service have been developed by EPCglobal Inc., and are well documented (e.g., [1]).

At UHF frequencies, tags primarily use electromagnetic coupling, which means that readers couple with tags primarily with propagating (TEM mode) electromagnetic energy in the far field, which is how these tags are able to achieve long read distances (30 ft is now common). However, when the tag is in the near field of the reader antenna, coupling occurs by multiple modes, including inductive coupling. One can design tags to couple with the reader antenna primarily with inductive coupling, giving rise to UHF near-field tags. These tags will be examined more in Section VI.

Since large numbers of tags are being used in the supply chain and tags have a relatively short useful life, they must have a low cost. This leads to very simple antenna designs, primarily strip-line dipoles. Also, since the 4-in label is an industry standard, most dipole antennas are meandered so that the total length is less than 4 in (e.g., see Fig. 1). Widths of 1/2 and 1 in are most common, but other sizes exist. Antennas are commonly made out of copper, aluminum, or silver ink, and include a number of competing low-cost materials and manufacturing techniques [4]. Antennas are typically attached to a polyethylene terephthalate (PET) film substrate, making the tag flexible. The IC is commonly prepared for attachment by adding small metallic bumps to the pads and connected to the antenna via a flip-chip assembly method and bonded with an epoxy. Alternatively, the IC is first bonded to a small interposer (or "strap") and then the interposer is bonded to the antenna. (The antenna in Fig. 1 was designed to be used with an interposer.) The resulting antenna, substrate, and IC is called an *inlay*, and it is common then to incorporate the inlay into a printable label with a pressure sensitive adhesive or encapsulate in some other way.

The simple and electrically short dipole antenna imposes important restrictions on the performance of tags. It is well known that dipoles have relatively narrow bandwidths, and short dipoles suffer from the problem of fractional bandwidth [12]. Thus, materials' large dielectric constants, large dielectric loss, and conductors can significantly affect the antenna efficiency as well as the impedance. Antennas are typically designed so that they present the complex conjugate of the IC impedance to maximize power delivered to the IC. The power transfer efficiency is given by $\tau = 4R_aR_c/|Z_a + Z_c|^2$ [12], where R and Z represent resistances and (complex) impedances, respectively, and subscripts a and c represent the antenna and chip (or "IC"), respectively. Deviations in antenna impedance from the complex conjugate of the chip impedance can significantly impact tag performance. The most common materials that negatively impact tag performance are metals and liquids, especially water. This has led to the well-known "metal/water problem."

A. Tags—Metal Water Problem

We can define the *effective gain* of the tag antenna as follows:

$$G_{\text{eff}} = D\eta\tau \tag{1}$$

where D is the directivity of the antenna, η is the antenna efficiency, and τ is the power transfer efficiency described previously. (Note that it is common to have a 3 dB mismatch between circularly polarized reader antennas and linearly polarized tag antennas.) When tags are placed near metal, a number of things happen. The directivity tends to increase, efficiency decreases from reduced radiating resistance, and the antenna impedance can change dramatically causing poor power transfer efficiency. We have found that some antennas that are intended to be used near metal are designed so that they are not resonant in free space, but maintain a small but suitable τ when near metal in order to maintain some level of performance.

Near water or other high-dielectric, high-loss material, directivity also increases, efficiency decreases because of dielectric loss. Since water has a large dielectric constant (approximately 80), dipole antennas placed near water undergo a significant shift in resonant frequency and may lose efficiency from not operating at a resonant mode, as well as a shift in antenna impedance negatively impacting τ.

This problem has led to a number of microstrip-based dipole antenna designs [5]–[9], but the increased complexity and material costs make them impractical for use in the supply chain, and thus outside of the scope of tags studied here.

B. Tags—Near-Field Coupling

There has been considerable interest recently generated in the industry over UHF near-field technologies, especially tagging high-value small goods at the item level, such as pharmaceuticals, jewelry, and electronics. Here, we define *near field* to mean that the primary coupling mechanism can be described predominantly using magnetic fields (although it is well known that the near-field may also include an electrostatic component). It is commonly taken that the near field is that area near the reader antenna less than $2D^2/\lambda$, where D is the largest antenna dimension, and λ is the free-space wavelength. When $D \approx \lambda/2$, as is common, the near-field is approximately $\lambda/2$, or 6.4 in (16 cm) at 915 MHz. Since coupling occurs primarily through magnetic fields, and since most nonmetallic materials have a

relative permeability of unity, these materials will not interfere with the coupling of the tag and reader antennas. Magnetic coupling has been used for decades in passive RFID, including LF (125–135 KHz) based on ISO standards 11784, 11785, and ISO 14223-1, HF (13.56 MHz) with ISO standards 14443 and 15693, as well as emerging standards such as IEEE P1902.1 (RuBee). Recently, near-field tags ISO 18000-6c are being manufactured and marketed for UHF tags. We discuss that more in Section VI.

C. Readers

Readers (interrogators) are used to power the tags, inventory tags in the field, and interface to a host PC or network using an API. While the software and middleware components of readers can be quite complex, in this paper, we focus on the basic ability of readers to read tags.

FCC regulations in the USA and similar regulations in other regions stipulate that the maximum allowable reader output power is 1 W with a maximum antenna gain of 6 dBi, yielding a 4 W effective isotropic radiating power (EIRP). In Europe, the ETSI regulation specifies a maximum of approximately 3.2 W EIRP. The reader transmits signals and a carrier wave to both instruct and power passive tags. It then listens for the backscatter modulation of the tags, implementing the protocol specification.

All the readers tested in this paper are "fixed" readers, meaning that they are capable of full output power and used efficient, directional antennas to approach the maximum allowable output power.

There are two common modes for implementing the antennas for RFID readers: monostatic and bistatic. A *monostatic* antenna is one in which the same antenna is used for transmission as well as receiving. A *bistatic* antenna uses two colocated antennas for separate transmit and receive. Conventional wisdom states that readers using bistatic antennas perform better than those using monostatic antennas. It is also common to use handheld readers, which can use lower-gain antennas and lower output power, but we do not study these here.

Within the tag-reader communication system, there is the reader-to-tag (forward) channel and the tag-to-reader (back) channel. One fundamental question is which channel tends to be the limiting factor. If the limiting element in the system is whether the chip gets sufficient power, then the forward channel will be limiting. If the chip responds but the reader is unable to detect the response, then the back channel is limiting. Conventional wisdom states that the tag-reader system is forward-link limited, which we find to be almost always false.

In the following few sections, we present a series of experiments to test tags. We return to reader performance in Section VIII.

III. Performance of Tags Near Metal

As described previously, one of the technical difficulties of low-cost passive UHF RFID tags is that metal can significantly degrade performance. However, there has been little work in quantitatively evaluating how much performance is degraded [11]. To address that question, we devised a simple experiment to determine how tag performance is affected by metal.

Devising an experiment to test performance is full of subtle difficulties, beginning with the definition of "performance." To simplify the measurements and results, we chose to take an end-user metric by defining *performance* of a tag to be the maximum read distance of a tag by a commercial reader in a given environment. This simple, high-level metric obscures more detailed information, such as frequency dependent information, signal strength, impedance mismatch, link limits, and cause of failure. While other metrics would be more precise, they would also fail to tell the "whole picture" in the complex tag-reader system. Whether and how the tag responds and whether the reader recognizes the response is a part of this performance metric, and not just whether the tag responds. We believe this simple, end-user metric is sufficient for illustrating the important aspects of performance. Other aspects are measured in the following sections.

Since we chose an end-user metric, then the performance must be qualified by the reader and environment. In this section, we chose the best-performing commercial reader (determined by other experiments) and placed in a laboratory room, a 13.5 × 25 × 18 ft (4.1 × 7.6 × 5.5 m) room with RF absorbing cones on the floor and back wall to reduce multipath affects. Although the cones absorb the majority of the radiation, it was not a fully anechoic environment. Note that all read distances were truncated at 25 ft because of the maximum room dimension.

We selected four "typical" tags from a pool of 14 commercially available tags. These include a large, 4 × 4 in (102 × 102 mm) tag, a 1 × 4 in (102 × 25 mm) tag, a 0.5 × 4 in (102 × 13 mm) tag (the form factor that is most commonly used in the supply chain), and a tag of approximately 1.5 × 1.5 in (38 × 38 mm). We have results from all 14 tags, and found that the most important aspect for determining performance behavior in various scenarios was the size of the antenna. Thus, these four form factors are representative of the larger trends and we make special note otherwise.

For this experiment, we placed each of the four tags in four scenarios: directly on a metal (copper) plate, separated by metal by a single thickness of 0.15 in (3.8 mm) corrugated fiberboard (sometimes called cardboard), separated by a double-walled 0.25 in (6.35 mm) corrugated fiberboard, and in free space. Tags were placed in optimal orientation. We measured the maximum read distance of each tag in our laboratory environment. Tests were repeated several times to validate repeatability of the results.

We hypothesize that the 4 × 4 tag will have the greatest read distance because it uses a dual-dipole design that can almost double the power harvesting ability of single-dipole designs; the 4-in tags will have equal read distance because they have equal effective gain; and the small tag will have a substantially reduced read distance because of a number of compromises that result in a degraded effective gain. Near metal, we expect more degradation with the smaller antennas and the smaller separations. The results are presented in Section VI.

The results show that no tag is readable when applied directly to metal. A single corrugated fiberboard layer is sufficient separation to allow the tags to be readable, but we observe that the read distance is reduced to between 68% and 88% for the 4-in tags, and 100% for the smaller tag. Note that the reduction in

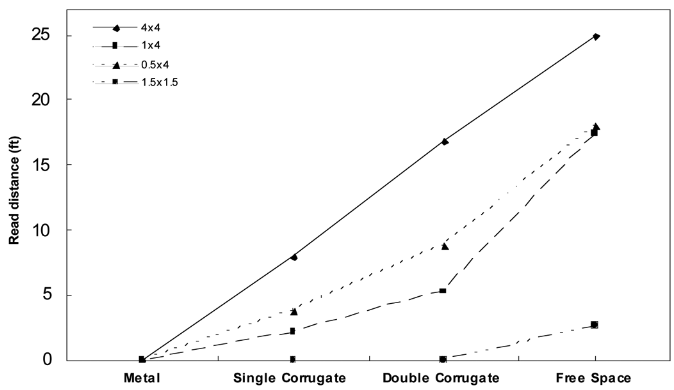

Fig. 2. Read distance of tags near metal.

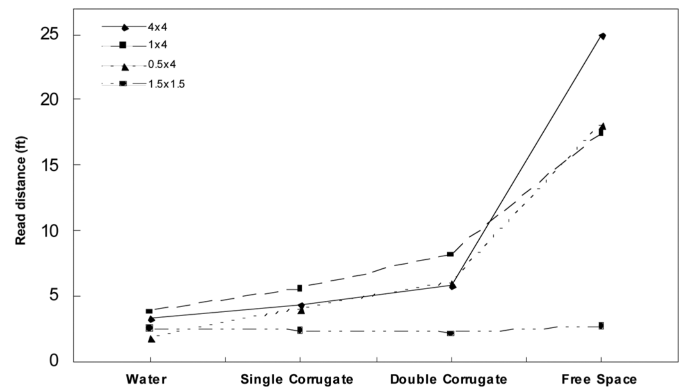

Fig. 3. Read distance of tags near water.

performance by the 4 × 4 tag (68%) may be larger because the free-space read distance was truncated to 25 ft. Increasing the spacing with double-walled corrugated fiberboard showed an increased performance, but still suffered between 38% and 70% reduction in the free-space read distance. These results indicate that conveyor applications may struggle to read cases filled with metal or foil-lined contents. Dock-door applications will certainly suffer with all but the largest 4 × 4 tag. Theses trends validate our initial hypothesis. Similar trends were observed when using plastic foam separation, so the results were omitted for brevity.

IV. Performance of Tags on Water

Water and water-based contents present another important challenge to UHF RFID tags. These include water-based material such as meats and produce, which are particularly important to track and trace, either for freshness or for product recalls. As we show here, water provides different challenge for passive UHF RFID.

We performed the same experimental process as described in Section III using the same tags in the same environment. The only difference is that we used a polypropylene box container with 0.05 in (1.27 mm) thick walls filled with tap water under room-temperature (70 °F) conditions. The tags were placed directly on the outside of the polypropylene container, separated by a single-layer corrugated fiberboard, double-layer corrugated fiberboard, and in free space. We had the same hypothesis as in Section III. The results are shown in Figs. 2 and 3.

Clearly, water degrades the tag performance significantly. Read distances were reduced to between 79% and 90% for the 4-in tags, but notably, we saw no degradation in read distance for the small tag. A single layer of corrugated fiberboard gave only a modest increase in performance, and we observe a reduction of 68% to 83% of the free-space read distance for the 4-in tag, and again, no reduction by the small tag. The double-walled corrugate increased performance only modestly, seeing a 53% to 77% reduction from the free-space read distance. (Recall again that the 4 × 4 free-space read distance was truncated to 25 ft.)

We note that, unlike metal, tags placed directly on water containers did yield some moderate level of performance. However, we observed that increasing the separation distance with corrugate did not yield the same increase in performance as it did with metal.

Finally, we note that the 1.5 × 1.5 tag performed radically different than the larger tags on both metal and water. Unlike the larger tags, the presence of metal completely disabled the small tag. However, water seemed to have little or no affect on the smallest tag. We can speculate that the small tag is an electrically short antenna is relatively inefficient in free space. As it is placed near metal, the Q of the antenna increases and it no longer becomes readable. Near water, however, the large dielectric constant effectively lengthens the antenna, simultaneously making the antenna closer to resonance and increasing the dielectric loss of the system.

V. Alternate Method of Evaluation

Conventional wisdom states that the limiting factor in RFID systems is the forward channel (getting sufficient power to the tag to operate the IC), and that if the reader is able to provide sufficient power to the IC, then there will be sufficient power in the return signal to communicate with the reader, i.e., the RFID system is strongly limited by the forward (reader-to-tag) channel power. If this is true, then we can use an alternative, simpler test methodology: we keep the tag-to-reader distance fixed and vary the output power of the reader. If this metric is sufficient, then it can automate the process of testing tags.

To test conventional wisdom, we tested tags under the two different methodologies in a side-by-side comparison. We used the same tags and separations near metal and water as before. This time, we used a reader utilizing a monostatic antenna. We chose to use a monostatic reader because it had been fully instrumented for this experiment. We placed the tag 1 m from the reader in a partially anechoic environment. We varied the output power of the reader in 0.5 dB increments and measured the minimum power level in which the reader was able to detect a single tag read in 256 read attempts. We then used the Friss equation to extrapolate the read distance

$$P_t = \frac{G_r P_r}{d^2} \frac{\lambda^2}{(4\pi)^2} \frac{G_{\text{eff}}}{P_{to}} \rho.$$

Here, G_r is the reader antenna gain, P_r is the reader's transmit power (that we varied), and d is distance. The second

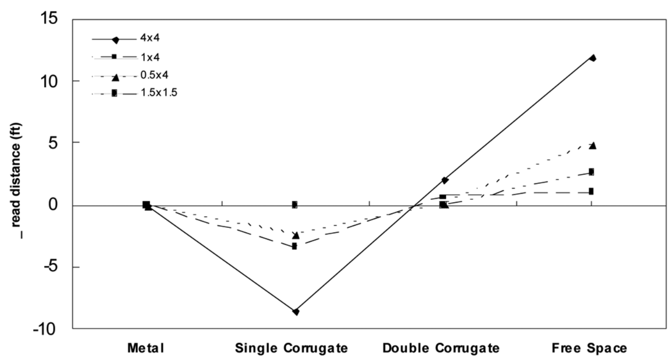

Fig. 4. Difference between measured and extrapolated read distance of tags near metal.

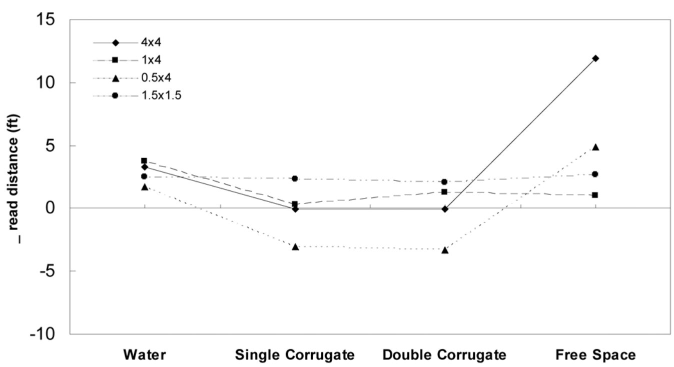

Fig. 5. Difference between measured and extrapolated read distance of tags near water.

term is the power-gain normalization constant. The third term defines the tag performance [$G_{\rm eff}$ is defined by (1)], and ρ is the polarization mismatch between reader (circular) and tag (linear) antenna assumed to be 0.5. While we do not directly measure the various tag parameters, we know the trivial relationship between transmit power, received power, and distance. By varying the transmit power until the tag turn-on power is achieved, we can estimate read distance. Clearly, this estimation relies on the assumption that the tag-reader system is limited by the forward link. (This method reduces the tag-to-reader free space path loss.) If the measured distance is less than the estimated read distance, then it is likely that the system is back-link limited. If the distances are equal, then the system is likely balanced or forward-link limited. If the measured distance is longer than the estimated distance, then there is likely some other confounding factor, such as the difference between monostatic and bistatic reader systems.

We placed the tag 1 m in front of the reader and varied the reader power to find the minimum reader power to be able to read the tag. Figs. 4 and 5 show the difference between the measured read distance (using the approach described in Sections III and IV) and the estimated read distance (varying P_r and estimating d). Note that this technique does not measure tag read distances less than 1 m.

What we see are inconsistent results. On metal, no tags were readable so there is no difference. With a single corrugate separator, the estimated distances were always further than measured, indicating a back-link-limited system. With a double corrugate spacer and in free space, however, as well as nearly all measurements on water, the measured read distance exceeds that of estimated. That indicates that there are limits in a monostatic reader system that are limiting, even if tags are placed 1 m away.

However, we can see a general trend: single corrugate spacing always yields the smallest difference and free space yields the largest. This may indicate that tags that are most detuned (smaller τ) tend to be more reverse-link-limited than tags in free space. Since the tag IC modulates its impedance to achieve backscatter communication, an antenna that is relatively far from a conjugate match may result in a very small backscatter modulation signal.

Earlier, we hypothesized that the extrapolated read distance will always yield better performance, which this data contradicts. Instead, it indicates that there are at least some instances in which tags are back-link limited, as well as showing an example in which a monostatic reader estimation is not as sensitive as a bistatic reader performing reads at distance. This topic is explored more in Section VIII.

VI. Near-Field Tag Performance

The novel argument in favor of UHF RFID is for the application of item-level tagging, e.g., tags less than approximately 25 mm^2. Since the wavelength at UHF frequencies is considerably smaller at HF or LF frequencies, the near-field is also typically small, and the read distance is expected to be about 6 in (15 cm). However, since the induced voltage is proportional to the square of the frequency, high-frequency magnetic coupling has a technical advantage within the usable distance. While most HF and LF tags require multiple loops to form the antenna in order to obtain a sufficiently large induced voltage, a single loop at UHF frequencies reduces the manufacturing complexity by eliminating the "cross-over" structures needed to connect the two ends of a loop with multiple windings.

The compelling question is whether UHF near-field tags "work," especially in the presence of metal and water. UHF near-field technology has recently been promoted within the industry as a technical solution to the "metal/water problem" (e.g., [10]). To test this, we obtained a commercial prototype of a UHF near-field reader antenna and five commonly available near-field tags. These tags ranged in size from 10 mm $\times$ 10 mm to 8 mm $\times$ 32 mm. Tags 1 and 2 were near-field only tags (i.e., consisted solely of a loop), while Tags 3–5 were combined near-field and far-field tags (i.e., included elements of a dipole). We label the tags in order of increased area. For this test, we used the vendor recommended reader, which was different than those readers used elsewhere in this paper, and operated the reader at full power (30 dBm). Again, we placed tags directly on metal, separated by a single corrugate layer, double corrugate layer, and in free space. We measured the maximum read distance (in inches) in which the tags could be read. The results are shown in Fig. 6. Similarly, we placed the tags on a water-filled container (0.050 in or 1.27 mm thick polypropylene), separated by a single corrugate layer, double corrugate, and again in free space. If market claims are correct,

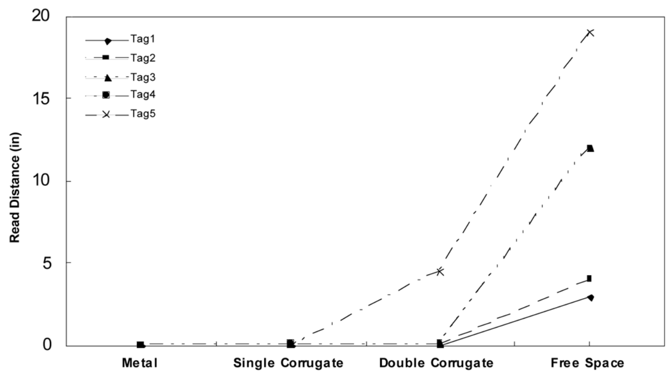

Fig. 6. Near-field tag performance near metal.

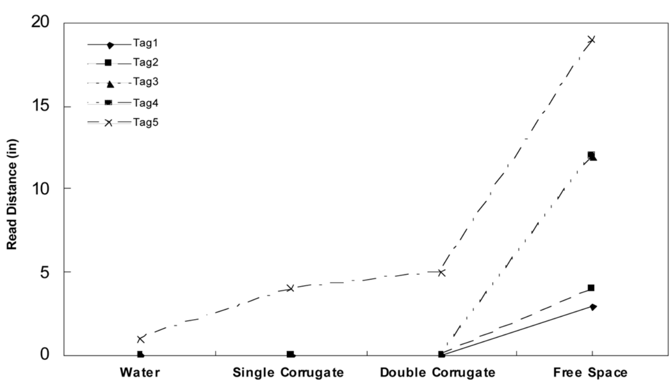

Fig. 7. Near-field tag performance near water.

we expect see less sensitivity to tags near metal and water. Those results are shown in Fig. 7.

The results clearly show that tag performance is radically affected by the presence of metal or water. Only Tag 5 was readable when close to metal or water. We speculate that Tag 5 performed well because coupling was primarily electromagnetic in nature.

Our evaluation of commercial near-field tags clearly shows that near field tags do not "solve" the metal-water problem. To the contrary, the presence of metal or water is shown to have more of a detrimental affect on near-field tag performance than far-field tag performance. We performed similar tests using HF (results not presented here) and showed that HF tags tend to be less affected by the presence of metal or water, but still more than that of UHF far-field tags.

One possible explanation for these results is that the reader antenna we used was a commercial prototype, and not working properly, but that explanation is not sufficient to explain the results. The reader was also different from the ones tested elsewhere. However, we emphasize that we performed the tests using vendor recommended reader, reader antenna, and tags.

While considerable work has been performed on evaluating HF and LF near-field antennas, we propose that a worthy research task would be to perform a rigorous analysis of the UHF near-field antenna analysis, especially in developing models that include the presence of metal or water near the tag antenna. We also assert that there is an important and unfulfilled need for

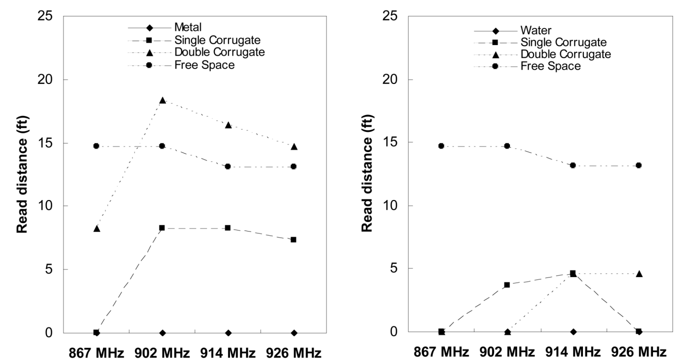

Fig. 8. Performance versus frequency of 4 × 4 tag.

the research community to educate the commercial sector about UHF near-field technology.

VII. Bandwidth Limitations

Earlier, we noted that dipole antennas are not broadband antennas, a problem that is exasperated by the dipole being electrically short. In particular, one of the difficult issues with UHF is that the available bands for operation vary with geographic location. Most of the world has adopted one or both of two frequency ranges, 864–870 MHz and 900–930 MHz, with Japan choosing to operate around 952–954 MHz. Generally, the specification calls for operation over 860–960 MHz, or about 11% bandwidth, which is a challenge for electrically short dipoles, and even more so when near metal or water. With supply chains commonly extending across multiple continents, world-wide operation of tags becomes an important, practical consideration. With this information, we hypothesize that tag performance will degrade rapidly away from the resonant frequency, since the antenna near metal or water will have a considerably larger Q (quality factor, or approximately the reciprocal of bandwidth).

At the time of the testing, our laboratory did not have the ability to test at 953 MHz. However, we were able to operate at 867 MHz as well as anywhere between 902 and 928 MHz. We tested the tags using the method described in Section V, but instead of frequency hopping over the entire FCC frequency band, we fixed the frequency at about 867, 902, 914, and 926 MHz. We used the same 4-in tags, and placed the tag directly on metal, separated from metal by a single and double corrugate layer, directly on the water container, separated from the water container by a single and double corrugate layer, and in free space. The results are shown in Figs. 8–10, with separations from metal shown on the left and separations from water on the right. The extrapolated read distance is shown in the Y-axis.

The results show a clear pattern. Obviously, performance degrades when placed near metal or water, as is shown by earlier experiments. Within the FCC band (902–928 MHz), there are small changes with respect to frequency for all of the tags. What is clear is that the behavior at 867 MHz is consistent: free-space performance was on par with the performance in FCC bands, but almost always degraded more at 867 MHz when placed close to metal or water.

These results verify our hypothesis that tags near metal or water will exhibit smaller bandwidths. This result points to an

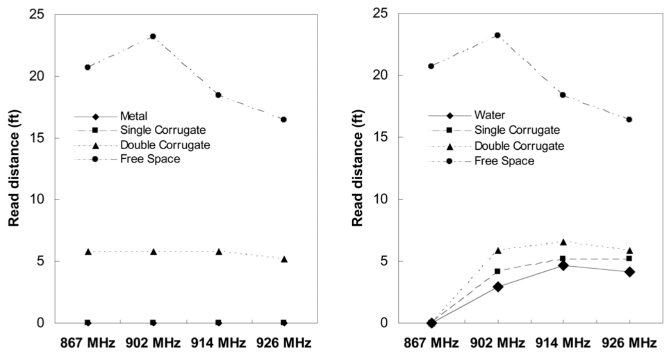

Fig. 9. Performance versus frequency of 1 × 4 tag.

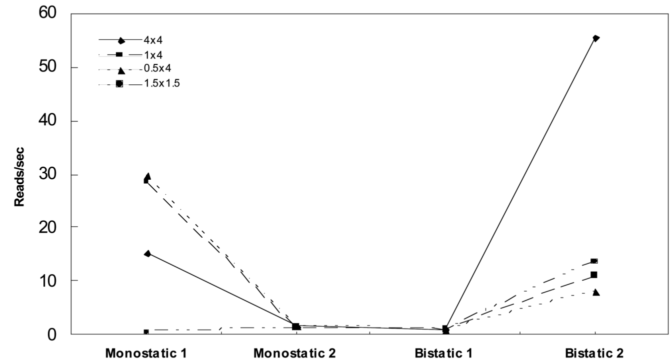

Fig. 11. Read speeds. Please see note for qualifying information.

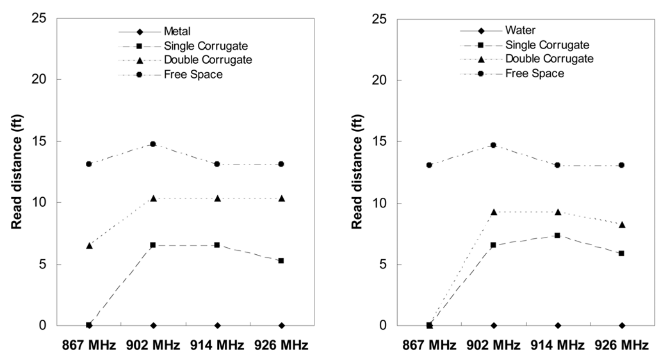

Fig. 10. Performance versus frequency of 0.5 × 4 tag.

important problem that needs to be addressed if RFID is to be implemented across global supply chains.

VIII. Performance of Readers

Previously, we have used read distance as the metric for tag/reader performance. Another metric of performance is how quickly readers can detect tags in various environments. In this section, we examine a number of different performance metrics for readers and show how they measure up to theoretical maximums.

A. Read Speeds

The ISO 18000-6c protocol allows for a variety of parameters, including tag-to-reader data rates, the use of a preamble, and the algorithm for controlling the number of slots in a randomized slotted Aloha ("Q") protocol [1]. However, we have found that, in general, readers offer little variety or control over these parameters. For example, although the tag-to-reader data rate may be set to between 5 and 640 kb/s, most readers use by default approximately 160 kb/s. Also note that readers are largely controlled by software and thus are highly configurable. We chose to use the factory-default settings as a baseline for comparison.

While the timing parameters to the protocols can vary substantially, as well as the length of the tag ID, it is possible that the readers can read over 1000 tags/s. What we observe is far lower than that. Our initial hypothesis is that read speeds will be dominated by the firmware/software of the reader. Since all the ICs designs implement the same standard, we do not expect that the read speeds will vary much by the tag, and certainly not by two tags using identical ICs.

For this experiment, we placed a tag 1 ft (0.3 m) from the reader in free space in order to place the tags well within the read field and to minimize the BER of the channel. We instructed the reader to read tags as rapidly as possible and record the number of reads. For many readers, software was provided that would perform that function, but for some we needed to write our own software to control the reader. Every effort was used to set the reader in the factory default mode and use the most efficient means of reading tags. We recorded the number of reads in 60 s to calculate the number of reads per second. The results of several commercially available readers are shown in Fig. 11. Here, the term "Monostatic" is used to identify a monostatic reader and "Bistatic" for a bistatic reader. Note that we suspect that the reader Bistatic1 aggregated multiple reads, and thus should not be used as a basis for comparison.

One can see that Bistatic1 and Monostatic2 showed fairly consistent results, and while Bistatic2 showed modest changes in read rates, Monostatic1 showed results that varied by more than a factor of 10. Bistatic1 showed a constant read rate, likely due to filtering of multiple reads.

We spoke with representatives from two of the reader manufacturers, and both indicated that this metric was *not* a good measure of the reader performance. The Gen 2 protocol specifies a set of commands and valid responses to those commands, but gives a great deal of freedom in how to inventory the tags in a region. These readers were programmed so that they spend a great amount of effort looking for new tags and little time looking for tags that they have already seen. Thus, the read speeds can appear quite low.

It should be noted that we have verified that all tags used the same IC, yet still resulted in considerably different read speeds. We have verified this behavior by constructing two different antennas and attach the same IC to the two antennas and observed differing read speeds. Recall that all the measurements here are taken with the tags 1 ft away from the reader antennas, and thus both the forward and reverse channels have excess capacity.

We must conclude that the tag-reader system is more complex than it initially appears, and the data presented here is inconclusive. We point out that developing high-quality, repeatable reader performance metrics is an important research activity for

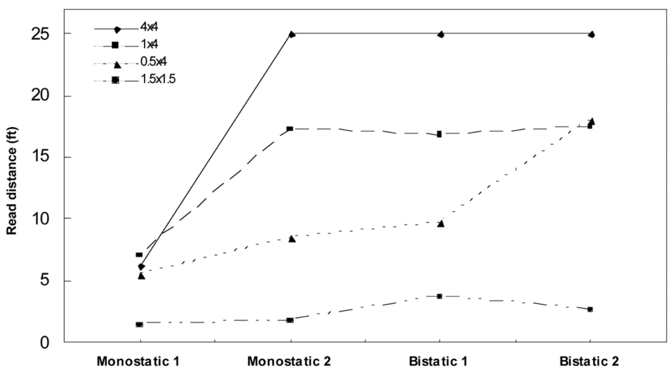

Fig. 12. Variation of performance with readers.

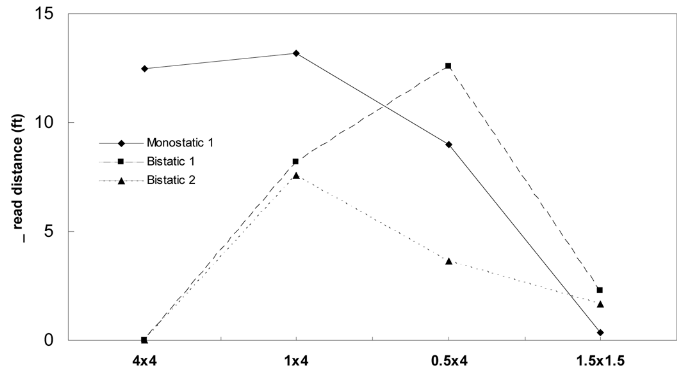

Fig. 13. Difference in performance between closed and open environment.

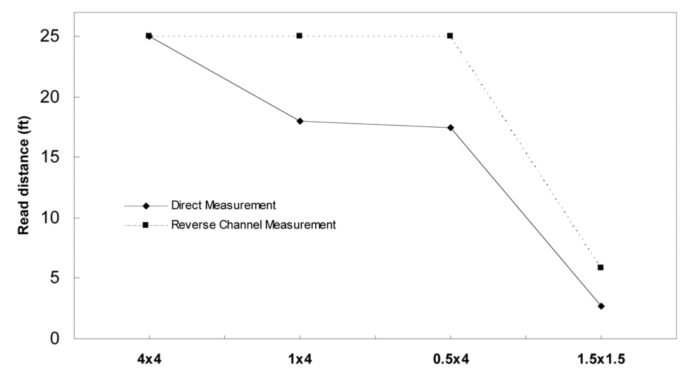

Fig. 14. Reverse channel experiment results.

validating reader performance, but inherently difficult because readers are so flexible with the firmware and software frequently changing.

B. Variation of Read Distance With Readers

Next, we want to see how much readers varied in their ability to read the same tags. This prompted us to use the same experimental setup as in Sections III and IV, placed the tags in free space, and measured the read distance. We conducted the tests in the same closed environment, the laboratory room with RF absorbing cones on the floor and back wall to reduce multipath affects. Conventional wisdom states that the tag-reader system is forward-link limited, so our initial hypothesis is that there would not be a significant difference in read distance between readers, especially if they all use the same output power. We used the same four tags as before. The results are shown in the graph in Fig. 12. Note again that the room size was limited to 25 ft, and thus measurements of 25 ft may be truncated of the actual read distance.

The results of Fig. 12 indicate that the readers using bistatic antennas are able to read tags significantly further than the reader using a monostatic antenna. Generally, bistatic readers perform the same or better than monostatic readers. We also see tag-reader pairs that show unique performance characteristics. For example, the reader Bistatic 2 best read the 0.5×4 tag, while Bistatic 1 best read the 1.5×1.5 tag.

These results indicate that the tag-reader system is *not* forward-link limited. It also indicates that some readers read some tags better than others. We explore this concept more in the following subsections.

C. Variation of Performance With the Environment

If the tag-reader system is not forward-link limited, then we are prompted to inquire to the degree in which the environment plays a factor in read distance performance. In this section, we repeated the same experiment as before but changed the environment. In one environment, we used the same "closed" environment (laboratory room). In the second environment, we used a large, open atrium to simulate an "open" environment. Care was taken to place the tags and readers in the same position so that the tagreader systems would use the same physical channel. If the system is reverselink limited, then the open environment will yield larger read distances. We used the three readers as before, and report the difference between read distances in the open and closed environments in Fig. 13.

The results show a clear bias of improved performance in the open environment, even for the bistatic readers that performed well in Section VIII-B. This is another strong indication that the tag-reader system is limited in the reverse link.

D. Reverse Channel Experiment

The results of the two previous experiments prompted us to perform one more experiment to determine how limited the system is to the reverse link. Normally, the bistatic antenna is physically in close proximity to each other, i.e., about 1 ft (30 cm), and are frequently housed in the same package. In this experiment, we used physically separated antennas for transmit and receive. We separated the tag from the transmit antenna, but placed the receiver antenna physically close to the tag so as to minimize the reverse-link loss. We performed the experiment in our laboratory (closed) environment, and present the results in Fig. 14. These results show again that the system is limited in the reverse link. By carefully comparing the difference in Figs. 13 and 14 with the 0.5×4 and 1.5×1.5 tags that the system is reverse-link-limited in the open environment. What these results clearly show is that there remains a significant challenge to develop better readers to read tags at long distances in closed environments.

IX. Conclusion

In this paper, we present a series of experiments to help understand the limitations and opportunities for contributions in

passive UHF RFID. We show that tag performance can degrade significantly near metal and water. Generally, larger tags yield better performance and that the smaller "item-level" tags are significantly poorer-performing than the 4-in tags. We also show that at 867 MHz, while performance in free space is comparable, performance near metal and water is drastically reduced. We also showed some early results that show that UHF near-field tag performance does not "solve" the metal/water problem, and indeed, shows more significant degradation in performance than far-field tags.

With readers, we show strong indications that the tag-reader system is reverse-link limited. Our tag read speeds test is inconclusive.

These results indicate that there is significant room for technical contribution on the following topics.

- A tag antenna that does not degrade near metal/water, but can meet the cost constraints of the supply chain.
- A tag antenna that can operate worldwide when placed near metal or water.
- A better understanding of UHF near-field, including its strengths and limitations as compared to UHF far-field, and those results communicated in a way that can be appreciated by practitioners.
- Improved algorithms for readers for use in "closed" and "noisy" environments. This is especially important as tag power requirements decrease.

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